Abstract

Adhesive bonding which has been in use for long as a traditional joining method has gained ground in the last couple of decades due to the introduction of advanced composite materials into the aerospace industry. Bonded structures have advantages such as high corrosion and fatigue resistance, ability to join dissimilar materials, reduced stress concentration, uniform stress distribution, good damping characteristics etc. They also have certain limitations like environmental degradation, existence of defects like pores, voids and disbonds, difficulty in maintenance and repair etc. A serious drawback in the use of adhesively bonded structures has been that there are no established comprehensive non-destructive testing (NDT) techniques for their evaluation. Further, a reliable evaluation of the effect of the existing defects on strength and durability of adhesive joints is yet to be achieved. This has been a challenge for the research and development community over several decades and hence, been the motivation behind this piece of research work. Under the scope of the work carried out in the thesis, some of the primary factors such as the existence of defects, degradation of the adhesive, stress and strain distribution in the bonded region etc., have been considered to study the bond integrity in composite to composite lap shear joints.

The problem becomes complex if all the parameters affecting the adhesive joint are varied simultaneously. Taking this into consideration, one of the key parameters affecting the bond quality, viz., the adhesive layer degradation was chosen to study its effect on the bonded joint. The epoxy layer was added with different, definite amount of Poly vinyl alcohol (PVA) to arrive at sets of bonded joint specimens with varied adhesive layer properties. A thorough review of different non destructive testing methods applied to this particular problem showed that ultrasonic wave based techniques could be the right choice.

To start with, preliminary experimental investigations were carried on unidirectional glass fiber reinforced plastic (GFRP-epoxy) lap joints. The adhesive joints were subjected to non destructive evaluation (NDE) using ultrasonic through transmission and pulse echo techniques as also low energy digital X-ray techniques. The results obtained showed a variation in reflected and transmitted ultrasonic pulse amplitude with bond quality. Digital X-Ray radiography technique showed a variation in the intensity of transmitted x-rays due to variation in the density of adhesive. Standard mechanical tests revealed that the addition of PVA decreased the bond strength. A plot of coefficient of reflection from the first interface and the bond strength showed a linear correlation between them.

After obtaining a cursory feel and understanding of the parameters involved with the preliminary experiments on GFRP adhesive joints which yielded interesting and encouraging results, further work was carried on specimens made out of autoclave cured carbon fiber reinforced plastic (CFRP)-epoxy bonded joints. Normal incidence ultrasound showed a similar trend. Analyses of the Acoustic Emission (AE) signals generated indicate early AE activity for degraded joints compared to healthy joints. Literary evidences suggest that the ultrasonic shear waves are more sensitive to interfacial degradation. An attempt was made to use oblique incidence ultrasonic interrogation using shear waves. The amplitude of reflected shear waves from the interface increased with an increase in degradation. Further, a signal analysis approach in the frequency domain revealed a shift in the frequency minimum towards lower range in degraded samples. This phenomenon was verified using analytical models. An inversion algorithm was used to determine the interfacial transverse stiffness which decreased significantly due to increase in degradation.

Conventional ultrasonic evaluation methods are rendered ineffective when a direct access to the test region is not possible; a different approach with guided wave techniques can be explored in this scenario. Investigations on CFRP-epoxy adhesive joints using Lamb waves showed a decrease in the amplitude of 'S_o' mode in degraded samples. Theoretical dispersion curves exhibited a similar trend. Frequency domain studies on the received modes using Gabor wavelet transform showed a negative shift in frequency with increased degradation. It was also observed that the maximum transmission loss for the most degraded sample with 40 percent PVA occurred in the range of 650 – 800 kHz. Non linear ultrasonic (NLU) evaluation revealed that the nonlinearity parameter (β) increased with increased degradation.

Kissing bonds are most commonly occurring type of defects in adhesive joints and are very difficult to characterize. A recent non-contact imaging technique called digital image correlation (DIC) was tried to evaluate composite adhesive joints with varied percentage of inserted kissing bond defects. The results obtained indicate that DIC can detect the kissing bonds even at 50 percent of the failure load.

In addition, to different experimental approaches to evaluate the bonded joint discussed above, the effect of degradation on the stresses in the bond line region was studied using analytical and numerical approach. A linear adhesive beam model based on Euler beam theory and a nonlinear adhesive beam model based on Timoshenko beam theory were used to determine the adhesive peel and shear stress in the joint. Digital image correlation technique was used to experimentally obtain the bond line strains and corresponding stresses were computed assuming a plane strain condition. It was found that the experimental stresses followed a similar trend to that predicted by the two analytical models. A maximum peel stress failure criterion was used to predict failure loads. A failure mechanism was proposed based on the observations made during the experimental work. It was further shown that the critical strain energy release rate for crack initiation in a healthy joint is much higher compared to a degraded joint.

The analytical models become cumbersome if a larger number of factors have to be taken into account. Numerical methods like finite element analysis are found to be promising in overcoming these hurdles. Numerical investigation using 3D finite element analysis was carried out on CFRP-epoxy adhesive joints. The adherend – adhesive interface was modeled using connector elements whose stiffness properties as well as the bulk adhesive properties for joints with different amounts of PVA were determined using ultrasonic inspection method. The peel and shear stress variation along the adhesive bond line showed a similar trend as observed with the experimental stress distribution (DIC) but with a lesser magnitude. A parametric study using finite element based Monte-Carlo simulation was carried out to assess the effect of variation in various joint parameters like adhesive modulus, bondline thickness, adherend geometrical and material properties on peel and shear stress in the joint. It was found that the adhesive modulus and bond line thickness had a significant influence on the magnitude of stresses developed in the bond line.

Thus, to summarize, an attempt has been made to study the bond line integrity of a composite epoxy adhesive lap joint using experimental, analytical and numerical approaches. Advanced NDE tools like oblique incidence ultrasound, non linear ultrasound, Lamb wave inspection and digital image correlation have been used to extract parameters which can be used to evaluate composite bonded joints. The results obtained and reported in the thesis have been encouraging and indicate that in specific cases where the bond line thickness and other relevant parameters if can be maintained or presumed reasonably non variant, it is possible to effectively evaluate the integrity of a composite bonded joint.